

**PROPERTIES OF MINOR IONS IN THE SOLAR WIND AND
IMPLICATIONS FOR THE BACKGROUND SOLAR WIND PLASMA**

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Annual Report on the grant NAG5-10996 "Properties of minor ions in the solar wind and implications for the background solar wind plasma"

1.1 Scope of the Investigation

The scope of the investigation is to extract information on the properties of the bulk solar wind from the minor ion observations that are provided by instruments on board NASA space craft and theoretical model studies.

Ion charge states measured in situ in interplanetary space are formed in the inner coronal regions below 5 solar radii, hence they carry information on the properties of the solar wind plasma in that region. The plasma parameters that are important in the ion forming processes are the electron density, the electron temperature and the flow speeds of the individual ion species. In addition, if the electron distribution function deviates from a Maxwellian already in the inner corona, then the enhanced tail of that distribution function, also called halo, greatly effects the ion composition.

This study is carried out using solar wind models, coronal observations, and ion calculations in conjunction with the in situ observations.

1.2 Progress Made During The Period 06/01 03 to 05/31 04

In previous studies we mostly focused on the fast solar wind originating from large polar coronal holes, and the properties of that type of wind from the coronal base outward. In the recent studies we have put more emphasis on the coronal properties of the slow solar wind (e.g. Chen, Esser and Hu, 2004) and on the properties of the fast solar wind in the chromospheric/coronal transition (e.g. Lie-Svendsen and Esser, 2004).

In both cases we made some very interesting discoveries. In case of the slow solar wind we were able to show that the wind speed varies non-monotonically with increasing distance in the source region, leading to a local minimum of the outflow speed near the streamer cusp point. In this study we made use of recent coordinated UVCS and LASCO measurements by Strachan et al. to constrain the heating parameters of a one-dimensional single-fluid minor ion model. We calculated the outflow velocity profile of O^{5+} ions in the flow tube overlying the helmet streamer which is supposed to be the source region of the slow solar wind at least during solar minimum. The background solar wind parameters and the flow tube geometry were taken from a recent two-dimensional magnetohydrodynamic solar wind model. We also showed that the observed effective temperature in the perpendicular direction (to the magnetic field) and the outflow speed of the O^{5+} ions can be used to put limits on their parallel thermal temperature. Some models are shown in figure 1 and compared to observations.

In collaboration with O. Lie-Svendsen from the Norwegian Defence Institute, we modeled the solar wind minor ions with a 16 moment solar wind model where we use one set of equations for each ion species of the same element (e.g. 15 sets of equations for Si). This model extends from the upper chromosphere to 1 AU and allows for a detailed consideration of the energy budget of the minor ion species. We find that the energy loss of the minor ions is smaller than the energy loss of the protons. This leads to higher minor ion perpendicular temperatures compared to the protons, even if the same amount of heat per particle is deposited into the ions as into the protons.

Once the oxygen ions decouple from the protons, they tend to become much hotter than the protons. With the highest heating rate, $C = 5 \times 10^{-18}$ W, the mean oxygen temperature exceeds 10^8 K. However, even for the lowest heating rate, $C = 2 \times 10^{-19}$ in the rapidly expanding geometry (which leads to a very low oxygen flow speed in the solar wind, $\bar{u} \simeq 150$ km/s, in the absence of additional heating further from the Sun) the maximum oxygen temperature in the corona is about 4 times higher than the maximum proton temperature. In this case there is no "preferential heating"

of the oxygen ions: Translating the mechanical energy flux deposited in the protons into a heating rate per proton we find that this heating rate has a maximum of about 5×10^{-19} W, or more than twice the $C = 2 \times 10^{-19}$ W per oxygen ion (see figure 2, from Lie-Svendsen and Esser, 2004). In a steady state system the oxygen temperature at a given location is determined by the balance between the energy sources and sinks. The high oxygen temperature, despite the low heating rate per particle, indicates that the energy loss per oxygen ion is much lower than for protons, unless the ion temperature becomes much higher than the proton temperature. The energy loss into the solar wind requires much higher temperatures for heavy particles than for light particles (protons). Since the loss is essentially given by “evaporating” particles with (thermal) speeds higher than the gravitational escape speed of the Sun, and the escape speed is independent of particle mass, the heavy particles require a higher temperature. Moreover, heat conduction is less important for heavy particles than for light particles. This case therefore illustrates that understanding the energy loss mechanisms for the heavy ions may be at least as important as understanding their heating mechanism. This result is important for the interpretation of the coronal minor ion observations.

During this study we also found that we can use the model to study the role of very rapidly expanding flux tubes in the upper chromosphere/low corona. This might lead to results that are potentially important for explaining the FIP effect and are certainly important for the coronal heating. If the fast wind originates in such flux tubes, which is commonly assumed in studies of the FIP effect, then this has serious consequences for the heating of the plasma. In this case a large amount of energy needs to be deposited in that rapidly expanding region. The question then is how that energy can be delivered to the system. We are currently the only group that has access to a solar wind model extending from the chromosphere to the corona and including all the necessary physics, such as anisotropies, heating, conduction equations and minor ions.

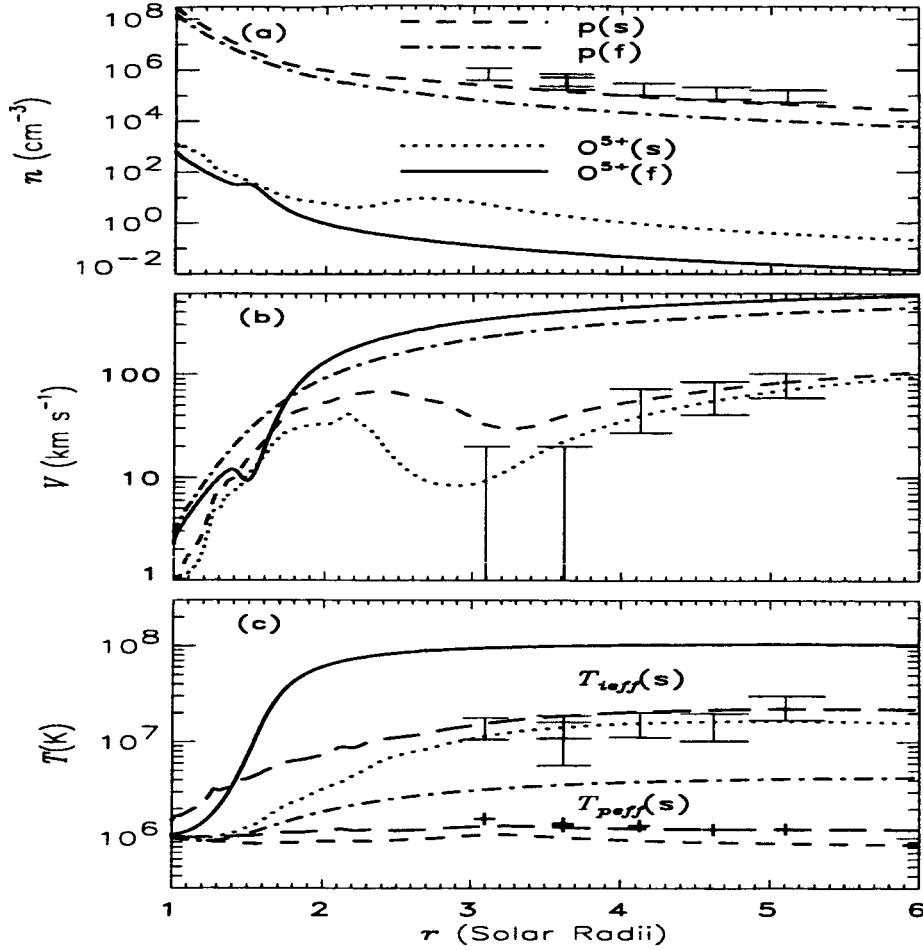


Fig. 1. Numerical solution for the O^{5+} ions in the fast(tube f) and slow(tube s) wind: (a) number density, (b) velocity, and (c) temperature. The long-dashed lines in panel c represent the modeled effective temperatures. The parameters for the protons are also plotted. The observational results for (a) the electron number density, (b) the O^{5+} outflow speed, and (c) the perpendicular effective temperatures of O^{5+} ions (error bars) and protons (plus signs) along a streamer axis beyond $3 R_S$ are taken from Strachan et al. (2002). The stagnation flow in the model seems to match the observations rather well.

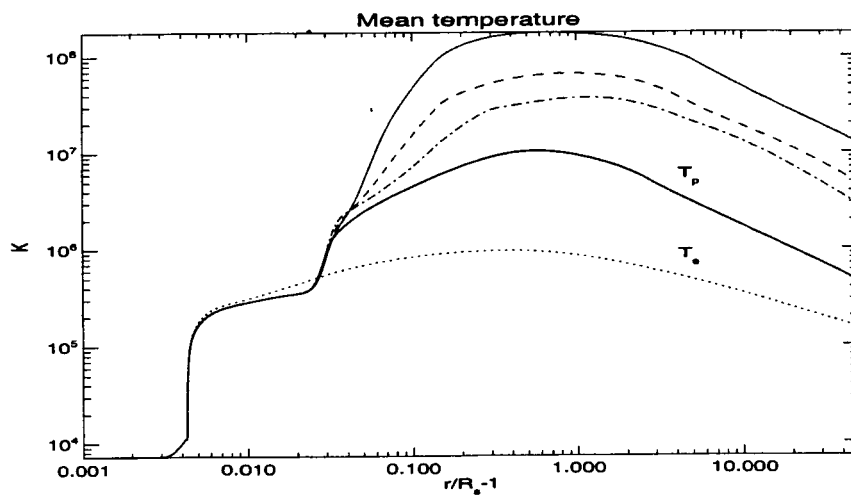


Fig. 2. Electron, proton and ion temperature. The heat is deposited into the ions in such a way that the heating per particle is larger for the protons (see text).

2. Publications in journals and talks presented at meetings fully or partially funded by the grant

1. Hu, Y.Q., S. R. Habbal, Y. Chen and X. Li, Are coronal holes the only source of fast solar wind at solar minimum? *J. Geophys. Res.*, **108**, pp. SSH 8-1, 2003.
2. Chen, Y., R. Esser, and Y.Q. Hu, Numerical modeling of the halo electrons in the fast solar wind, *J. Geophys. Res.*, **108**, pp. SSH 7-1, 2003.
3. Esser, R., O. Lie-Svendsen, R. Edgar, and Y. Chen, Observational and theoretical constraints on the heating and acceleration of the fast solar wind, *Proceedings of the Tenth International Solar Wind Conference. AIP Conference Proceedings, Volume 679*, pp. 249-254 (2003).
4. Habbal, S. R. et al., On the Detection of the Signature of Silicon Nanoparticle Dust Grains in Coronal Holes, *The Astrophysical Journal*, Volume 592, Issue 2, pp. L87-L90, 2003.
5. Chen, Y., R. Esser and Y. Hu, MHD Modeling of the Halo Electrons in the Fast Solar Wind, *American Astronomical Society, SPD meeting 34*, 06.09, 2003.
6. Chen, Y., R. Esser, L. Strachan and Y. Hu, Stagnation flow of O^{+5} ion in the source region of the slow solar wind, *Astrophys. J.*, **602**, 415, 2004.
7. Esser, R. von Steiger, R., Preface to: COSPAR session: Streamers and the slow solar wind, *Advances in Space Research*, Volume 33, Issue 5, p. 667-667, 2004.
8. O. Lie-Svendsen and R. Esser: "Modeling the energy budget of solar wind heavy ions: Implications for temperatures and abundances", presented at EGU meeting, Nice, 2004.
9. O. Lie-Svendsen and R. Esser: "Gyrotropic modeling of minor ions in the solar corona: Changes in abundances and temperature with heating rate.", to be submitted to *Astrophys. J.*, 2004.